Upper Air Wind Speeds Calculated from Observations of Natural Infrasound[1,2]

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ABSTRACT

In a continuing study of the feasibility of using microbarom (natural infrasound) observations to define characteristics of upper air winds, we determined the seasonal mean trace velocity of microbaroms. We show that this is equal to the acoustic velocity at an upper reflection level. This velocity is the sum of the sound speed based on temperature alone and the wind speed. We determine the former from the vertical temperature profile and can thus calculate the wind speed at particular reflection levels in the stratosphere and ionosphere. Our results compare well with direct observations.

1. Introduction

This is a continuing study of what can be learned about the upper atmosphere by monitoring the characteristics of microbaroms. Microbaroms are infrasonic waves (5-sec period) radiated into the atmosphere by interfering ocean waves in marine storm systems.

In a recent paper (Donn and Rind, 1972) we showed how variations in recorded microbarom signal level are related to varying wind directions at different levels in the atmosphere, in particular between 40–70 km and 100–120 km elevation. Our results agreed with observations made by active experimental methods. Our prime

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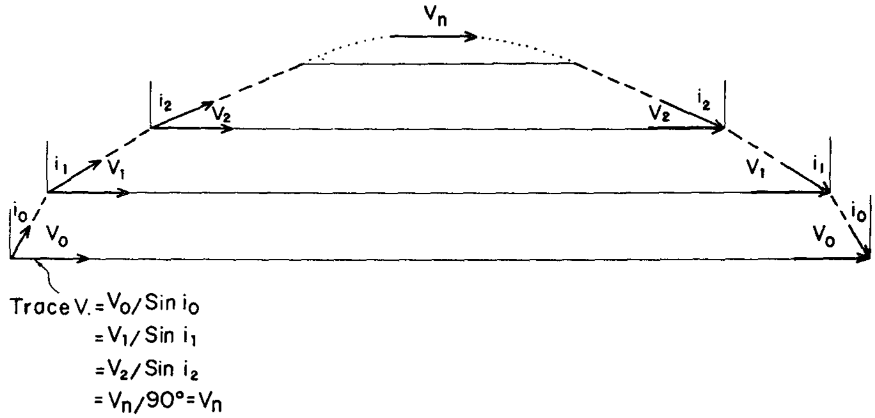

FIG. 1. Schematic representation of acoustic ray path from source to receiver due to progressive refraction. Layered atmospheric model is shown with straight ray segments and constant horizontal trace velocity.

result showed that microbarom signal strength was greatly enhanced when propagation direction coincided with upper wind direction, thus permitting these directions to be determined by this passive infrasonic probe.

In this continued study we determine upper wind speeds as well as directions from microbarom properties.

2. Procedure

A tripartite array of capacitor microphones in 1000-ft noise-reducing pipes (line microphones) is maintained near Lamont. Output is telemetered to the Laboratory for direct visual recording as well as recording on analog magnetic tape for subsequent analysis. A SAICOR analog computer performs rapid spectral analysis and cross correlation of signal channels on taped or on-line information. Transducers are spaced at about a half-wavelength for 5-sec acoustic waves. For our array this spacing gives optimum resolution for the purpose of correlation.

Cross correlation of coherent microbaroms on pairs of channels leads to computations of the horizontal or trace velocity. This is the apparent velocity along the horizontal if sound is approaching at some vertical angle. For acoustic waves of microbarom period, phase and group or signal velocities are equal; hence problems of dispersion do not arise.

3. Theory

Consider an atmospheric model in which the sound velocity varies only in the vertical direction. Then, according to Snell's law, for each sound ray segment that undergoes refraction in such an atmosphere

$$\sin(i_0/v_0)=\sin(i_1/v_1)=\sin(i_2/v_2)=\text{constant}, \quad (1)$$

where the i's are the angles of incidence and the v's the different sound velocities in discrete small layers (see Fig. 1). The iterative use of Snell's law is made possible by the slowly varying nature of the atmospheric sound channel. In effect, we are approximating the real atmosphere of continuously varying sound velocity and hence curved sound rays by the use of a multi-layered atmosphere of constant sound velocity in each small layer having straight-line, sound-ray segments as in Fig. 1. As long as the speed of sound is constant over a wavelength (in this case the order of a kilometer) this approach is applicable.

As noted, trace velocity is the apparent horizontal velocity and is what is actually measured at the surface. The trace velocity for each ray segment (see Fig. 1) is given by

$$V_0/\sin i_0,\ V_1/\sin i_1,\ V_2/\sin i_2, \text{ etc.}$$

From this and from Eq. (1) we see that in an atmosphere in which sound velocity varies only along the vertical, the trace velocity in the layers are equal. As the ray becomes more horizontal at its apex, the trace velocity equals the effective sound velocity of the medium there. Hence, by measuring the trace velocity at the surface we obtain the sound velocity at the reflection height.

The acoustic velocity vector at the reflection level is the sum of sound speed (c) as a function of temperature only and the wind velocity component in the direction of propagation (w). The measured trace velocity is thus $c+w$. If we know the reflection level and its temperature (or c) we can obtain w.

Two uncertainties are introduced in this procedure: 1) the exact reflection level must be estimated and 2) the temperature at this level must be known precisely. The reflection level is estimated by use of the procedure described in Donn and Rind (1972). We employ a modified version of the acoustic ray-tracing program of Pierce (1966), including probable wind profiles from direct measuring techniques and temperature profiles from the *U. S. Standard Atmosphere Supplements* (1966) for the appropriate season at 45N. In regular use, when

TABLE 1. Mean trace velocity, sound speed and upper level winds.*

	Number of cases	Mean trace velocity	Standard deviation	Computed reflecting level (km)	Speed of sound** at reflecting level	Computed wind at reflecting level	Observed wind at reflecting level
Winter	99	339	41.3	105/115	310/348	30/9	30/0?
Summer	52	368	24.4	45	329	39	37

* All speeds in meters per second.
** A function of temperature.

source and receiver points were known, we found the program to be very accurate.

Because the temperature-wind data for the upper air are variable and scattered in time, their seasonal means seem to be the most representative. Therefore, in this work we calculated seasonal means of microbarom trace velocities. In this initial study we concentrated on the extreme seasons of winter and summer as the reflecting levels (due to winds) are well separated vertically.

4. Results

By incorporating the known summer winds and temperatures into the ray-tracing program, upper level reflections of infrasound from the east are obtained as given in the ray diagram of Fig. 2. Rays are plotted at 10° intervals of angles of incidence. Note the stratospheric reflection about 45 km, a result of the stratospheric easterlies in summer. The combined effect of temperature and wind [details given in Donn and Rind (1972)] causes reflection to occur in a rather thin layer. Greater resolution than that reproduced here shows that rays with angles of incidence $<64°$ are not reflected below 125 km, at which height dissipation effects strongly attenuate the signal (Donn and Rind). The

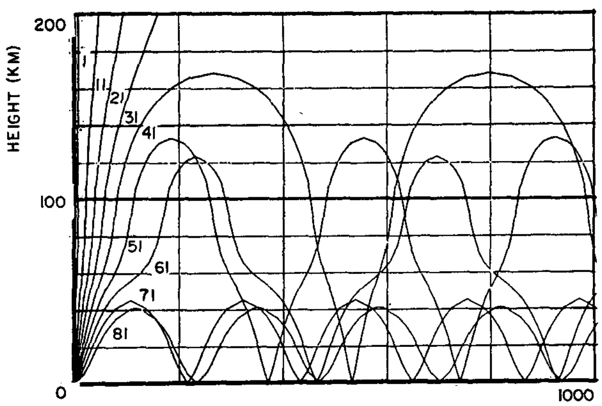

FIG. 2. Ray tracing diagram using best known summer winds and temperatures for a point source to the east. Stratospheric easterly winds help provide for reflection of certain rays from a narrow layer around 45 km. Numbers next to the rays indicate angle of incidence.

results to be considered below for the summer season thus appear to apply to a rather limited zone at about an elevation of 45 km.

Velocity results for both summer and winter are shown in Table 1. Also given here are standard deviation trace velocities, the reflection level with its sound speed (c), and the computed and observed wind speeds.

In summer, at 45N and 45 km elevation, the speed of sound due to temperature alone is 329 m sec^{-1}. As the trace velocity indicates that the average sound velocity at the reflecting level is 368 m sec^{-1}, the east wind over our region at 45 km was $368-329=39$ m sec^{-1}. The closest location to ours at which measurements are routinely made is Wallops Island, Va., about 3° of latitude to the south. Observations for July for 1961–68 (Meteorological Rocket Network Firings, 1969) indicate a mean wind from the east of 37 m sec^{-1} at this altitude. The agreement with that predicted for our location is obviously very good. We note also the relatively small standard deviation of the trace velocity for this season. This agrees well with the observed steadiness of the zonal component at 45 km in summer.

During the winter a strong semidiurnal variation of microbarom amplitudes occurs. We showed (Donn and Rind) that this variation is related to the variation in direction of the rotating semidiurnal tidal winds in the upper atmosphere. Maximum microbarom signal strength occurs when winds are from the east at about 105 km (1000 and 2200 LST). Minimum reception occurs about 0700 and 1800 LST when the wind pattern is such as to cause reflection from above 115 km, a zone of great dissipation for the frequencies involved.

The mean trace velocity in winter (Table 1) is 339 m sec^{-1}. Because the trace velocity has not been observed to vary significantly with time of day this mean value has been taken to be representative of any hour. For times of maximum microbarom signal strength, the speed of sound at 105 km has been estimated (with uncertainty) to be 310 m sec^{-1}, resulting in a computed east wind (339–310) of about 29 m sec^{-1}. This agrees with the observations collected by Rosenberg (1966) for middle-latitude winter winds at 100–105 km, although it is somewhat less than reported for specific locations by other sources (e.g., Wright, 1968).

For times of minimum microbarom signal strength, the speed of sound at 115 km is estimated (again with uncertainty) to be 348 m sec^{-1}. As the mean trace velocity applied to these times is 339 m sec^{-1}, light winds are indicated for this elevation. This agrees with available observations for the winter evening (Rosenberg, 1966).

A knowledge of the trace velocity and level of reflection thus appear to be sufficient to calculate the wind speed at reflection heights, giving results consistent with more direct observations.

One caution is necessary; as shown by Posmentier (1968) a close broad source can cause phase velocities (and thus trace velocities) to be overestimated by the array method, especially as the legs of the array become oriented more parallel to the ray path from the source. The use of pairs of microphones arranged normal to the ray path introduces other errors as they will have the lowest coherency. For our array, these facts may explain a few abnormally high velocities recorded from the southeast.

The results shown strengthen our suggestion that a synoptic network of microbarom observations can provide much information on the wind velocity at elevations up to 120 km.

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